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Damage Characterization of Dental Materials in Ceramic-Based Crown-like Layer Structures

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Abstract. A materials perspective of layered dental material systems representing tooth and crown structures is presented. In this study, failure modes in model bilayers and tri-layers with relatively hard, brittle ceramic (veneer and veneer/core) outer-layers on soft, tough (dentin-like) under-layers are evaluated. Contact testing simulating dental function on model layer systems with selected monolith or double-layer ceramic plates bonded to transparent polycarbonate substrates is used as a means for investigating the evolution of clinically relevant fracture modes. Data for the critical contact loads to initiate different damage modes in the ceramic layers are presented. These data quantify resistance of any given dental material to lifetime-threatening damage, especially subsurface radial cracking (but also other, upper-surface modes), thereby providing a sound basis for materials selection and design. We demonstrate how such data may be used to rank dental ceramics for damage resistance. The role of controlling material properties in determining damage resistance, especially strength, will be discussed.

Introduction

Ceramic-based layer structures are appealing for their chemical durability, their hardness, and their aesthetics. These are important issues in biomechanical applications, such as dental crowns and hip replacement prostheses. However, ceramics are also brittle, and are therefore susceptible to premature failure. In dentistry, the lifetimes of the latest all-ceramic crowns remain inferior to those of more traditional metal-core crowns. Research is now being conducted to determine the failure mechanisms

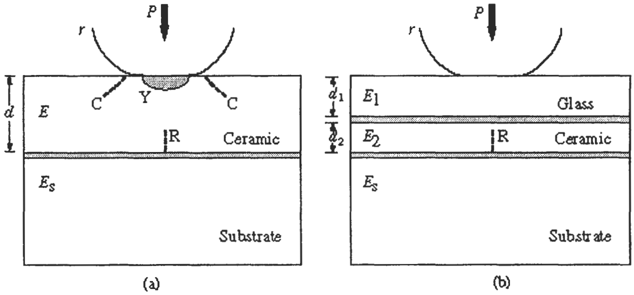

Fig. 1. Schematic of bilayer (a) and trilayer (b) structures, indented with sphere of radius *r* at load *P*. In (a) bilayer structure, a ceramic layer of thickness *d* is bonded with thin adhesive onto a thick soft substrate. Showing: surface cone cracks (**C**), and quasiplastic yield zone (**Y**) on the top surface and radial cracks (**R**) at the inner-surface. In (b) trilayer structure, glass veneer layer 1 (E_1) is bonded onto dental ceramic layer 2 (E_2) and then bonded on the same soft substrate polycarbonate. Showing radial cracks occur (**R**) in the second coating layer, (**C**) and (**Y**) are not shown.

in ceramic layer structures on dentin-like substrate structures, so that longer-lasting crowns may be produced in the future. Which material combinations, and what layer thicknesses, produce the best performance?

In this work it is demonstrated how contact tests on simple model bilayer and trilayer structures can provide valuable physical insight into failure modes in all-ceramic dental crowns. The model structures consist of monolith [1] or double-layer [2] ceramic plates (simulating crowns) bonded to transparent polycarbonate substrates (simulating dentin). The transparency of the polycarbonate base is useful for *in situ* observations of the subsurface radial cracks. Hertzian contacts (simulating oral function) produce concentrated loads on the structures. We show how these contacts can induce cracks and quasiplasticity at the ceramic top surfaces and radial cracks at the core ceramic lower surfaces (Fig.1). These damage modes, especially the subsurface radial cracks, are believed to be the principal cause of failure in dental crowns [3,4]. Critical loads to produce each damage mode are measured in the model layer systems. Fracture mechanics relations are developed for each mode, and are used to provide a basis for designing the next generation of layer structures with improved properties.

Fracture Mechanics

Bilayers. Consider the ceramic/soft-substrate bilayer structure in Fig.1(a). Closed-form relations expressing critical loads for cone cracks (C), quasiplasticity (or yield, Y) and radial cracks (R) in terms of basic materials properties and key geometrical variables have been reported for single-layer ceramics on soft substrates [5]. Defining an "effective sphere radius" $r = 1/(1/r_c + 1/r_i)$ and "effective coating modulus" $E = 1/(1/E_c + 1/E_i)$, where subscripts c and i refer to ceramic and indenter materials respectively, we obtain the following key critical load relations:

Cone cracks initiate from the top ceramic surface outside the contact circle, where the tensile stress is maximum. The critical load is

$$P_C = A(T^2/E)r \tag{1}$$

where T (K_{Ic}) is the ceramic toughness and A is a dimensionless constant.

Quasiplasticity initiates when the maximum shear stress in the Hertzian near-field exceeds $Y/2$, with yield stress $Y \sim H/3$ determined by the ceramic hardness H (load/projected area, Vickers indentation). The critical load is

$$P_Y = DH(H/E)^2 r^2 \tag{2}$$

with D another dimensionless constant.

Radial cracks initiate spontaneously from a starting flaw at the lower ceramic surface when the maximum tensile stress in this surface, from flexure of the ceramic on the soft support, equals the bulk flexure strength σ_F at load

$$P_R = B\,\sigma_F\,d^2/\log(CE_c/E_s) \tag{3}$$

with d the ceramic layer thickness and B and C further dimensionless constants.

Thus, given basic material parameters, one can in principle make *a priori* predictions of the critical loads for any given bilayer system, once the constants A, B and D are known. These relations, within the limits of certain underlying assumptions, have been verified for model ceramic/substrate bilayer systems [5].

Trilayers. Consider the ceramic/ceramic/soft-substrate trilayer structure in Fig.1(b). These structures are much more complicated to analyze than bilayers. A previous experimental study [2] indicates that whereas cone cracks and quasiplasticity form much as in bilayers, radial cracks are more likely to initiate first in the core support layer, even though the core is generally much stiffer and stronger than the veneer. This is because the stiffer ceramic core layer supports the bulk of the flexural load, making it more susceptible to fracture.

Ideally, it would be desirable and logical to derive a modified expression for trilayer similar to that of eqn. 3 for bilayers, i.e.

$$P = B^* \sigma_F d^2/\log(CE^*/E_s) \qquad (4)$$

where $B^* = B^*(\delta,\varepsilon)$ and $E^* = E^*(\delta,\varepsilon)$ are functions of Young's modulus ratio $\varepsilon = E_1/E_2$ and thickness ratio $\delta = d_1/d_2$ (subscripts 1 and 2 denoting veneer and core layers respectively). It is a requirement that such an expression should reduce to the bilayer solution at $\varepsilon = 1$ or $\delta = 0$. Thus, once the functions $B^*(\delta,\varepsilon)$ and $E^*(\delta,\varepsilon)$) are known, predictions could be made directly from bilayer results. In principle, such functions might be found from the theory of bilayer plates on soft foundations, but so far only finite element solutions have been obtained.

Experiments and Analysis

Bilayers. Bilayers were prepared as polished ceramic plates of thickness from $d = 100$ μm to 7 mm, which were bonded with epoxy adhesive ~ 10 μm thick to transparent polycarbonate substrates of thickness 12.5 mm, for *in situ* observation during indentation [5]. These bilayers were subjected to indentation with WC spheres of radius $r = 3.96$ mm. Radial crack initiation and evolution was monitored from below the contact through the transparent sublayer using a video tape recorder [1]. Critical loads P_R for radial cracking were determined directly from the video tape, for a minimum of 5 indentations at each thickness condition.

An *a posteriori* procedure was used to determine critical loads P_C for cone cracking and P_Y for quasiplasticity in the ceramic layers [6]. Rows of indentations were made on each ceramic surface at incrementally increasing peak loads, and the indented surfaces examined in an optical microscope. Values of P_C and P_Y were determined from ring crack traces and residual impressions on the top ceramic surfaces.

Results of critical loads measured in this way are shown in Fig. 2, as a function of ceramic layer thickness d, for six dental ceramics. Data points are critical loads for first damage: at large d (unfilled symbols), either cone cracking (P_C) or quasiplasticity (P_Y), whichever occurs first (quasiplasticity in all ceramics except porcelain); at small d (filled symbols), radial cracking (P_R). The lines are corresponding predictions from eqns. 1–3, for $r_c = \infty$ and $r = r_i$ and using known material parameters. Note that the P_C and P_Y data are insensitive to d, whereas the P_R data are highly sensitive, covering a range of more than 2 orders of magnitude.

Trilayers. Trilayers were prepared is a similar manner to the bilayers, except that now a glass veneer (simulating porcelain) was bonded to a dental alumina core before joining to a polycarbonate base. The thicknesses d_1 and d_2 of veneer and core were varied, but always keeping the total thickness of the double layer fixed at $d = d_1 + d_2 = 1.5$ mm (typical crown thickness). In these experiments the glass top surface was pre-etched to eliminate flaws using 4% Hydrofluoric Acid Gel (Bisco, Inc, IL, USA), to avoid top surface cone cracking and thus to allow uninterrupted viewing of subsurface radial cracks in the second layer. Indentation with WC spheres was again used to induce the fractures. Viewing through the transparent polycarbonate substrate confirmed radial cracking in the core ceramic undersurfaces, and enabled appropriate measurement of critical loads to initiate the cracks.

Critical loads PR from these experiments are shown in Fig. 3 as a function of glass and slip-cast alumina thicknesses d_1 and d_2. The value of P_R diminishes from the alumina/polycarbonate bilayer value on the right axis ($d_2 = 1.5$ mm), falling to a much reduced value at small d_2. Note, however, that the data appear to plateau out in the thickness regions from 0.1 mm to 1.0 mm, suggesting that the thickness ratio is not critical in a wide region. The solid curve through the data is the FEM calculation for this system. The critical loads from FEM are computed by equating the maximum tensile stress at the undersurface of the core layer, to the strength of the alumina (~ 500 MPa).

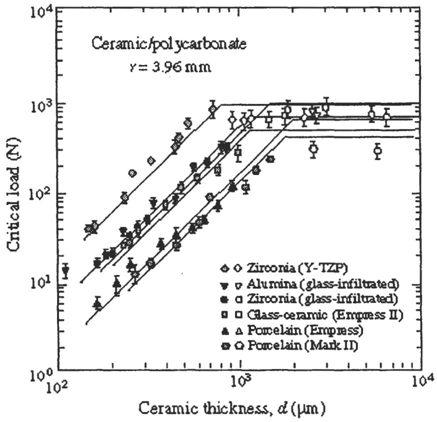

Fig. 2. Critical loads for first damage in ceramic/polycarbonate bilayers as a function of ceramic coating thickness d, for indentation with WC spheres of $r = 3.96$ mm. Filled symbols are P_R data, and unfilled symbols for P_C and P_Y data. Solid lines are theoretical predictions for radial (R) and cone cracking (C) and quasiplasiticity (Y).

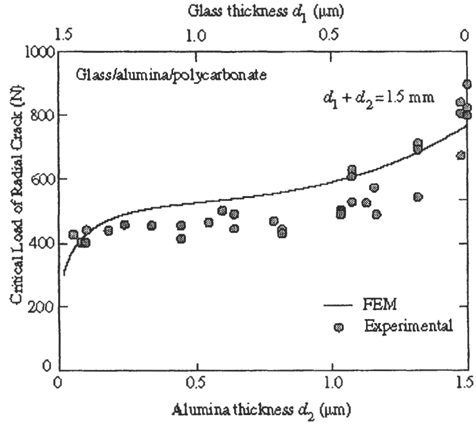

Fig. 3. Critical loads for radial cracks occurred in the second layer of coatings in glass / alumina / polycarbonate trilayer structure, as a function of alumina thickness d_2. Total thickness of glass and alumina layer is kept constant as 1.5 mm. Solid line is the calculation from finite element modeling.

Discussion

The results described in this work are useful for identifying competing modes of damage in bilayer and trilayer structures that simulate biomechanical systems, particularly dental crowns. Model layer systems consisting of single and double ceramic layers on soft polymeric substrates have been used to quantify the critical loads to produce each damage mode — cone cracking and quasiplasticity at the ceramic top surfaces and radial cracking at the lower surfaces. Most important is avoidance of subsurface radial cracks, because of their capacity to lead to premature failure of the composite layer structure. Fracture mechanics relations, eqns. 1–3, are able to account for the observed data trends, for different ceramic materials and different layer thicknesses. In principal, all that is required to calculate critical loads for a given layer system is knowledge of basic material parameters (modulus, hardness, strength, toughness).

The data in Fig. 2 are useful for predicting the responses of ceramic-based bilayers to contact loads [7,8]. Radial cracking becomes especially dominant at ceramic layer thicknesses $d < 1$ mm approximately, depending on the material. It is clear that some ceramics (especially Y-TZP zirconia) incur damage at higher critical contact loads than others (porcelain, Empress glass-ceramic); other ceramics (slip-cast alumina and zirconia, Empress II) lie in the intermediate region. Hence Y-TZP might appear to be the ceramic of choice for bilayer coating systems, since it would be resistant to radial cracking at much smaller thicknesses for any prescribed applied load (typically, 100 N for dental crowns). Of course, this is contingent on satisfying other functional properties for a given system—alumina tends to be more chemically inert, for instance, and thus could prove to be a compromise material in some applications (e.g. hip components).

Similarly, the data in Fig. 3 could prove useful in determining the responses of ceramic based trilayers. For a fixed net thickness $d = d_1 + d_2 =$ constant, replacement of the upper portion of a stiffer alumina core support layer with a glass veneer top layer reduces the critical load for radial cracking relative to that for the reference alumina/substrate bilayer, as may be expected. However, the data show relative insensitivity to the glass thickness d_1 over a broad range of intermediate values. This indicates that the relative thickness d_1/ d_2 of the two layers is not crucial to survival of the trilayer system, a useful conclusion in relation to dental crown preparation. A promising feature of the fracture mechanics approach outlined in relation to eqn. 4 is that one may be able to predict the complete response of trilayer systems a priori from analogous bilayer data, once the functions $B^*(\delta,\varepsilon)$ and $E^*(\delta,\varepsilon)$have been determined. In the absence of such functions, we remain constrained to finite element modeling for specific case studies.

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